Low-lying T=0 states in the odd-odd N=Z nucleus 62 Ga

Physics Letters B 726 (2013) 665–669

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Low-lying T = 0 states in the odd–odd N = Z nucleus ^{62}Ga

H.M. David [a,∗,1], P.J. Woods [a], G. Lotay [a], D. Seweryniak [b], M. Albers [b], M. Alcorta [b], M.P. Carpenter [b], C.J. Chiara [b,c], T. Davinson [a], D.T. Doherty [a], C.R. Hoffman [b], R.V.F. Janssens [b], T. Lauritsen [b], A.M. Rogers [b], S. Zhu [b]

[a] University of Edinburgh, Edinburgh, EH9 3JZ, United Kingdom
[b] Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] University of Maryland, College Park, MD 20742, USA

ARTICLE INFO

Article history:
Received 16 August 2013
Received in revised form 20 September 2013
Accepted 23 September 2013
Available online 30 September 2013
Editor: V. Metag

Keywords:
Isospin
N = Z
Levels
Shell-model
IBM-4

ABSTRACT

New, low-lying levels in the odd–odd, N = Z nucleus ^{62}Ga have been identified using a sensitive technique, where in-beam γ rays from short-lived nuclei are tagged with β decays following recoil mass identification. A comparison of the results with shell-model and IBM-4 calculations demonstrates good agreement between theory and experiment, with the majority of predicted low-lying, low-spin T = 0 states now identified. There is a dramatic change in the level density at low excitation energies for the N = Z nucleus ^{62}Ga when compared with neighbouring odd–odd Ga isotopes where, in contrast, the low-lying level structure is dominated by configurations with T = 1 pairing interactions between excess neutrons. This illustrates the distinctively different aspects of nuclear structure exhibited by nuclei with N = Z.

Self-conjugate nuclei play an especially important role in nuclear structure. A recent example is the observation of a highly enhanced Gamow–Teller β-decay transition from the ground state of the heaviest known N = Z nucleus, ^{100}Sn [1]. In such nuclei, the protons and neutrons occupy the same orbitals resulting in strong spatial overlap, and leading to amplification of nuclear structure effects. Odd–odd, N = Z nuclei have a specific importance as states with isospin T = 0 and T = 1 have similarly low excitation energies. Indeed, above ^{40}Ca, ^{58}Cu is the only known odd–odd N = Z nucleus with a T = 0 ground-state configuration [2]. Many theoretical frameworks have been developed to probe the structure of heavy N = Z nuclei, including shell-model calculations either with a direct diagonalisation of the Hamiltonian [3] or using Monte Carlo techniques [4,5], BCS or HFB calculations extended to incorporate T = 0 and T = 1 pairing correlations [6,7], and Isospin Invariant Interacting Boson Model calculations (IBM-4) [8]. A higher density of low-lying, T = 0 states is predicted in all calculations of odd–odd N = Z nuclei than currently observed. This is not thought to represent intrinsic deficiencies in the models, but rather a selectivity in the levels identified by experiments performed to date [8]. In the current Letter, we report new results on the low-lying structure of the odd–odd, N = Z nucleus ^{62}Ga using a sensitive experimental technique, wherein a variation of the recoil decay tagging method (RDT) [9,10] using positrons as the tag (RBT) [11,12] has been allied with a mass-separator device for the first time, thus allowing extremely clean γ-ray spectra to be generated.

The low-lying yrast level structure of ^{62}Ga was first identified by Vincent et al. in a γ-ray spectroscopy study using a heavy-ion fusion-evaporation reaction [13]. This structure was confirmed, and a number of non-yrast T = 0 states were identified in ^{62}Ga for the first time, in a measurement by Rudolph et al. [14]. In the latter work [14], potential candidates for low-lying T = 1, 2^+ and 4^+ states were also reported. However, despite this progress, ambiguities remained and a number of states predicted by theory were not identified.

In the present experiment, a beam of 103-MeV ^{40}Ca ions from the Argonne ATLAS accelerator bombarded a ∼ 490 μg/cm^2-thick ^{24}Mg target to produce ^{62}Ga nuclei via the 1p1n fusion-evaporation channel. Prompt γ rays were detected by the Gammasphere array [15,16], consisting of 96 HPGe Compton suppressed detectors. Recoiling reaction products with mass A = 62 and charge state 18^+ were transmitted to the focal plane of the Fragment Mass Analyzer (FMA) [17], where slits were employed to reduce contributions from neighbouring mass groups and scattered beam

∗ Corresponding author.
E-mail address: hdavid@anl.gov (H.M. David).
1 Present address: Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA.

0370-2693/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2013.09.054

particles. The mass-to-charge ratio of transmitted recoils was measured at the focal plane of the FMA by a parallel-grid avalanche counter (PGAC), which also provided timing information. A transmission ionisation chamber (IC) was installed downstream of the PGAC to measure energy loss which provided discrimination between recoils and scattered beam particles. Finally, the recoils were implanted into a highly-segmented double-sided Silicon strip detector (DSSD) of area 64×64 mm^2 and thickness 1 mm, consisting of 160×160 strips of 400-μm pitch. This DSSD was designed to provide high sensitivity for correlations between relatively short-lived ($T_{1/2} \sim 100$ ms) implanted ions and their subsequent β decays. Implantation rates were kept below 200 Hz in order to ensure background-free singles γ-ray spectra.

Tagging with short-lived β decays has been successfully implemented previously, but allied to a gas-filled rather than mass-separator device, where an additional selection of β decays with high-energy positrons was applied for background reduction [11,12]. Here, the use of mass separation largely eliminates the flux of strongly-produced, non-isobaric residues at the focal plane, allowing direct mass selection (and identification) of the recoils. The reduced background of both implant and decay events at the focal plane greatly improves the cleanliness of correlations between short-lived implanted ions and their subsequent decays, allowing the generation of extremely clean γ-ray spectra without relying on the detection of high-energy positrons.

The present experiment was performed with newly-installed digital acquisition systems for Gammasphere, the FMA ancillary detectors and the DSSD, based on the electronics developed for the GRETINA array [18]. Low event rates allowed the experiment to be carried out with a trigger requirement of a single signal in either Gammasphere or the DSSD, resulting in a maximum flexibility in the offline analysis. Efficiency and energy calibrations for γ rays were carried out with standard ^{152}Eu and ^{56}Co sources. Values of angular correlation ratios $R_{32:90}$, given by the ratio of the γ-ray intensity measured at $\sim 32°$ to the intensity measured at 90°, were used to establish the multipolarity of transitions with sufficient statistics. $R_{32:90}$ values of 0.72(4) and 1.15(3) for pure $\Delta I = 1$ and $\Delta I = 2$ lines in ^{62}Zn, respectively, were used for reference. The full level scheme of transitions observed in the present work for ^{62}Ga is found in Fig. 1.

Fig. 2 presents a γ-ray spectrum in coincidence with recoils that were followed within 400 ms by a β decay measured in the DSSD in a position not further than one pixel removed from the recoil implantation position. This requirement selects γ rays from short-lived ^{62}Ga nuclei ($T_{1/2} = 116.121(21)$ ms [19]). The position of the β decay is defined as the DSSD pixel where a maximum energy is deposited, since the β particles in general have a long range compared to the pixel dimensions. Choosing a smaller correlation area was found to reduce the correlation efficiency and was not needed for background reduction purposes. A spectrum of background lines from isotopes such as ^{62}Zn ($T_{1/2} \sim 9$ hours) and ^{58}Ni (stable), produced in the 2p and α2p evaporation channels, was obtained by correlating recoils with β decays occurring between 1 and 1.4 s after implantation. This spectrum was subtracted from that in Fig. 2. There is, for example, no evidence in Fig. 2 for the most intensely produced γ ray at 954 keV associated with the $2^+ \to 0^+$ transition from ^{62}Zn. Furthermore, the measured half-life of $T_{1/2} = 116.15(13)$ ms for the β decays associated with the γ-ray transitions of Fig. 2 is in good agreement with the literature value for ^{62}Ga [19]. Fig. 2, therefore, represents an essentially pure spectrum of ^{62}Ga.

Looking at the peaks annotated in Fig. 2, one can see three transitions not reported in earlier studies [13,14] at energies of 183, 590 and 979 keV. The 590-keV γ ray was observed in coincidence with the known 571-keV transition from the first excited

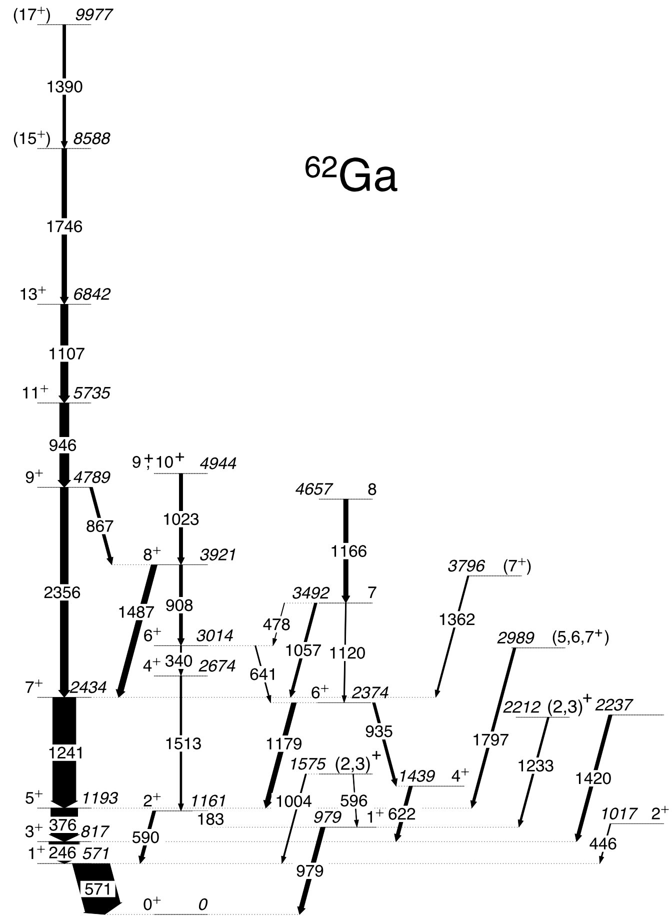

Fig. 1. Level scheme of ^{62}Ga; the width of the arrows is proportional to the relative intensities of the transitions. Further details can be found in Table 1.

state to the ground state, but not with other higher-lying yrast transitions, as shown in Fig. 3(a). This indicates that this 590-keV line feeds the 1^+ state at 571 keV directly from a new, low-lying level at 1161 keV. The direct feeding is confirmed by the line shape of the 571-keV γ ray in Fig. 3(a), which does not exhibit the low-energy tail observed for this transition when fed through the 3^+ yrast level at 817 keV (see Fig. 1), which is isomeric with $T_{1/2} = 3.2(11)$ ns [13]. A value of $R_{32:90} = 0.72(21)$ for the 590-keV transition rules out a stretched-E2 character at the 2σ level and is consistent with $\Delta I = 1$ dipole radiation. The ~ 200-keV energy difference between the 2^+ state at 954 keV in ^{62}Zn and the level at 1161 keV in ^{62}Ga precludes a $T = 1$ assignment for the latter state. The 1161-keV level is, therefore, assigned as $T = 0$. The expected dominant branch from the lowest-lying $T = 0$, 2^+ level is to the first excited 1^+ state [14], consistent with the dominant 590-keV γ ray from the newly-observed 1161-keV state. No direct branch to the ground state is predicted from this level [14], which is consistent with its non-observation here.

Fig. 3(b) provides a spectrum obtained by applying a coincidence gate on the 979-keV transition. The 183-keV γ ray is clearly observed in coincidence. Neither the 183- nor the 979-keV line is coincident with known yrast transitions and it is concluded that these γ rays emanate from the same, new 1161-keV level mentioned above. Relative intensities of 2(1)% and 17(2)% for the 183- and 979-keV transitions, respectively, indicate that the 183-keV line feeds a new level at 979 keV. The $R_{32:90} = 0.77(25)$ value for the 979-keV transition is indicative of $\Delta I = 1$ character, implying a 1^+ assignment for the level as states with negative parity

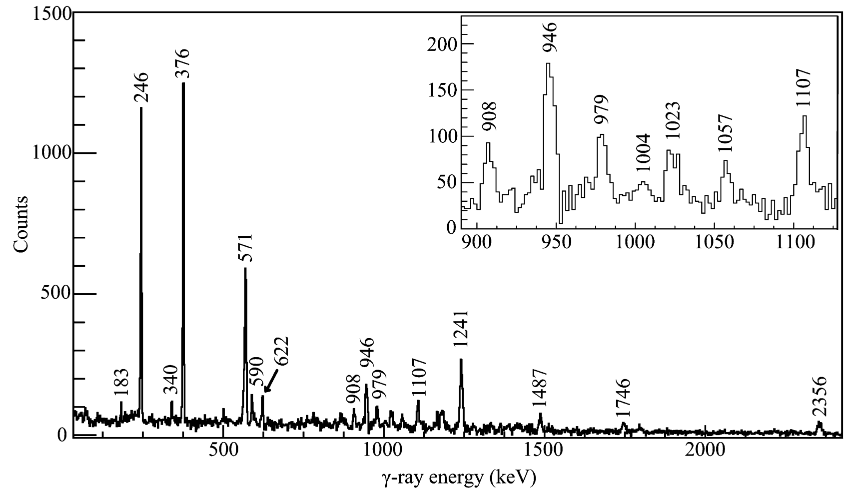

Fig. 2. Singles γ-ray spectrum in coincidence with recoils correlated with a β particle within 400 ms of implantation into the same DSSD region. The inset provides a detailed view of the $\sim$ 1-MeV energy region. The spectrum has been background-subtracted as described in the text and all transitions are assigned to ^{62}Ga.

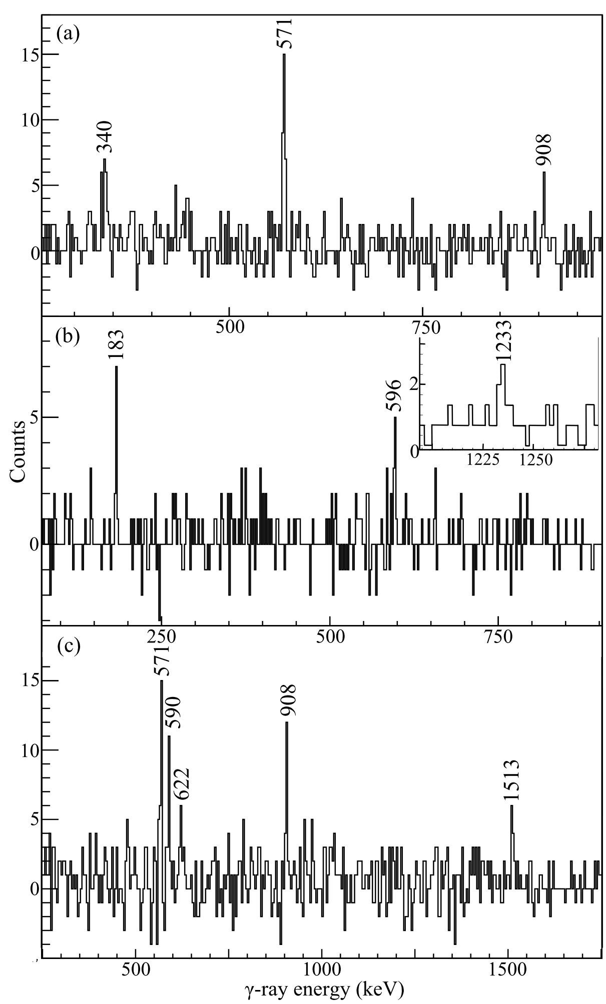

Fig. 3. Coincidence γ-ray energy spectra corresponding to recoils correlated with a β particle detected within 400 ms of implantation into the same DSSD region. (a) presents coincidences with the 590-keV transition, (b) coincidences with the 979-keV transition (a higher-energy region is detailed in the inset) and (c) coincidences with the 340-keV transition.

are not expected this low in excitation energy. A 1^+ assignment is consistent with the observation of a 979-keV γ ray reported by Grodner et al. [20] following the β decay of ^{62}Ge (although, in this case, no level scheme was reported), implying an allowed Gamow–Teller transition to the 979-keV state.

Fig. 3(c) presents γ rays in coincidence with the 340-keV transition first reported from a level at 3014 keV by Rudolph et al. [14]. The known 908-keV line links to a higher-lying 8^+ state at 3921 keV, as assigned in [14]. Here, a new 1513-keV transition is observed from a level at 2674 keV that links to the new 1161-keV state. This implies a sequence of three stretched-E2 transitions starting from the 8^+, 3921-keV level and ending on the 2^+ state at 1161 keV. Rudolph et al. proposed possible 6^+ or 7^+ assignments to the 3014-keV level, consistent with the 6^+ assignment proposed here [14]. The present data require the existence of a 4^+ state at 2674.0(17) keV. Rudolph et al. [14] reported a level at 2674.5(3) keV, based principally on a low-intensity transition at 1481 keV, with $\Delta I = 1$ character, to the 5^+ yrast state at 1193 keV. No evidence was found for such a transition, but it would likely be on the margins of observability in the present experiment. Hence, no firm conclusion can be drawn on its existence. Such a transition would be consistent with the current 4^+ assignment for the 2674-keV level, although $I = 6$ is assigned in [14], presumably based on yrast feeding arguments. The known 622-keV transition from the decay of the 1439-keV level [14] is observed as a weak peak in Fig. 3(c), suggesting an unobserved link with the state at 2674 keV. In the work of Rudolph et al. [14], a very weak linking transition at 1236 keV was tentatively reported, which would most likely be beyond the limit of sensitivity here.

Returning to the 979-keV transition, coincidence relationships are clearly found with a new γ ray at 596 keV (see Fig. 3(b)), implying a new low-lying level at 1575 keV. The 596-keV line is also evident as a high-energy tail on the 590-keV peak in the γ-ray singles data. The existence of this 1575-keV level is supported further by the observation of a weak line at 1004 keV, see inset of Fig. 2, which is found to be coincident with the 571-keV, $1^+ \to 0^+$ transition. The statistics are too low for both transitions from the 1575-keV state to draw any conclusion based on the angular distributions. A new γ ray at 1233 keV was also observed in coincidence with the 979-keV transition, as seen in Fig. 3(b), and assigned to the decay of a new state at 2212 keV.

Concerning the high-lying yrast structure, γ rays at 1746.2(8) keV and 1389.7(8) keV were observed in coincidence with yrast transitions, allowing an extension of the yrast band reported in [13,14] to states at 8587.7(11) keV and 9977.4(15) keV. This is in agreement with yrast transitions at 1747 and 1387 keV

Table 1
Properties of low-lying levels in ^{62}Ga obtained in this study. Previous results from Ref. [14] are given in the first two columns. Where information is consistent with the work of Rudolph et al. [14], but no new information on I^{π} assignments has been obtained in the present work, the assignments from [14] are quoted.

E_x (keV) Previous	E_γ (keV) Previous	E_x (keV) Present	E_γ (keV) Present	I_{rel} (%)	$R_{32:90}$	I_i^π	I_f^π
571.2(1)	571.2(1)	571[a]	571[a]	135[b]		1^+	0^+
817.2(1)	246.0(1)	817[a]	246[a]	112[b]		3^+	1^+
		978.8(4)	978.8(4)	17(2)	0.77(25)	1^+	0^+
1016.7(3)	445.5(3)	1017.1(7)	445.9(7)	2(1)[c]		2^+	1^+
		1161.0(3)	182.8(1)	2(1)		2^+	1^+
			589.5(3)	12(1)	0.72(21)	2^+	1^+
1193.5(2)	376.3(1)	1192.9(2)	375.7(1)	100(2)	1.21(11)	5^+	3^+
1439.4(2)	622.3(1)	1439.1(2)	621.9(2)	13(1)	1.26(36)	4^+[e]	3^+
		1575.1(7)	595.9(9)	3(1)		$(2,3)^+$	1^+
			1004(1)	5(3)		$(2,3)^+$	1^+
		2211.5(5)	1232.7(3)	7(4)[c]		$(2,3)^+$	1^+
2234.0(5)	794.4(5)	2237.3(17)					
	1417(1)		1420.1(17)	13(4)[c]			3^+
2373.6(3)	934.2(4)	2373.8(4)	935.3(4)[d]	10(1)		6^+	4^+[e]
	1180.1(3)		1179.4(7)	18(3)[c]	0.60(22)	6^+	5^+
2434.3(2)	1240.7(2)	2433.5(3)	1240.6(2)	87(3)	1.20(18)	7^+	5^+
2674.5(3)	1236(1)	2674.0(17)					
	1481(1)						
			1513.0(17)	7(3)		4^+	2^+
		2989.4(9)	1796.5(9)	10(1)		$(5,6,7^+)$	5^+
3014.8(3)	340.4(2)	3014.3(14)	340.1(3)	5(1)		6^+	4^+
	641.2(2)		641(2)[d]	4(2)[c]		6^+	6^+
3491.8(3)		3491.5(5)	478.3(11)	2(1)[c]		7	6^+
	1057.6(2)		1057.4(5)	10(1)		7	7^+
	1118.2(2)		1120.3(12)[d]	11(3)[c]		7	6^+
		3795.7(7)	1362.2(7)	6(2)		(7^+)	7^+
3922.0(3)	907.3(3)	3920.6(5)	907.6(5)	12(2)		8^+	6^+
	1487.7(3)		1486.9(5)	22(3)		8^+	7^+

[a] Energies taken from Ref. [14] as the isomeric nature of the 817-keV state prevented precise energy measurements of the 571- and 246-keV transitions in the current work.
[b] Relative intensity estimated from Ref. [14].
[c] Relative intensity estimated using γ-ray coincidences.
[d] Transition observed in the current work and placed in the level scheme based on previous observations reported in Ref. [14].
[e] A possible 5^+ assignment was also considered for this state in Ref. [14], but was "rejected due to the predicted [higher] energy".

previously reported in Ref. [21]. A summary of the transitions and levels reported here is found in Table 1 and compared with the data of Rudolph et al. [14]. In general, the agreement between the two studies is good.

The observation of the new, low-lying levels in the present study is most notable. The present methodology provides particularly clean identification of the specific reaction channel corresponding to ^{62}Ga, allowing almost background-free singles γ-ray data. In comparison, Rudolph et al. [14] detected light evaporation particles for channel selection. This results in higher efficiency, but relatively increased background from more strongly-produced reaction channels. Consequently, triple coincidences were required, in general, to generate clean γ-ray spectra for ^{62}Ga. This latter approach is, therefore, most sensitive to strong, high-multiplicity cascades of γ rays.

The 1017-keV state is particularly interesting as it was tentatively assigned as the lowest-lying $T = 1$, 2^+ state by Rudolph et al. [14]. This level was identified through a 446-keV, $\Delta I = 1$ transition to the first excited 1^+ state at 571 keV in γ–γ coincidence data. The signature for the $T = 1$, 2^+ state would be a relatively pure isovector M1 transition to the $T = 0$, yrast 1^+ level and a direct stretched-E2 decay to the ground state [14,22] (the latter branch was not observed in [14], as discussed below). In contrast, the $T = 0$, 2^+ level is predicted to have a strong E2 admixture to the yrast 1^+ state and no branch to the ground state [14]. A 1017-keV γ ray was indeed subsequently observed in a study of the β decay of ^{62}Ge by Grodner et al. [20], although no assignment was proposed. In an investigation of the analogous β decay from the $T = 1$, 0^+ ground state of ^{62}Ga to $T = 1$ states in ^{62}Zn, performed by Finlay et al., by far the most intense γ-ray transition observed was from the lowest-lying 2^+ state [23]. One would, therefore, expect such a transition to be observed following β decays to excited states in ^{62}Ga (along with γ rays following feeding of $T = 0$ levels in ^{62}Ga). The observation of a 1017-keV line in the data of [20], therefore, lends further support to a $T = 1$, 2^+ assignment for the 1017-keV level. In the in-beam γ–γ coincidence data, observation of the branch to the ground state is challenging since this direct decay is not coincident with yrast transitions. This branch is not seen in the present experiment in the singles spectrum of Fig. 2, but neither is the weak 446-keV line which is only observed in the γ–γ coincidence data (see Table 1), in agreement with the study of Ref. [14]. In the experiment of Ref. [20] there is significant background at energies below 511 keV, which hinders the observation of the 446-keV transition and no such line is reported [20]. It would be desirable, in future work, to observe both decay transitions in the same experimental study.

Considering the $T = 1$, 2^+ assignment favoured for the 1017-keV level, this implies a positive Coulomb Energy Difference (CED) of 63 keV compared to the analogous state at 954 keV in ^{62}Zn [24]. A positive shift is in keeping with trends observed for $N = Z$ nuclei in both the sd and fp shells, although the value itself is rather large compared with the 20–30-keV shifts exhibited by nuclei with similar mass [11].

Fig. 4 compares the low-lying levels in ^{62}Ga with shell-model [8,13] and IBM-4 [8] calculations. The former calculation incorporates an existing effective interaction in the $pf_{5/2}g_{9/2}$ space obtained by the Strasbourg group (see [25] and references therein). The IBM-4 Hamiltonian is also obtained from this effective interaction by a mapping procedure that relies on the existence of approximate shell-model symmetries [8]. There are no parameters

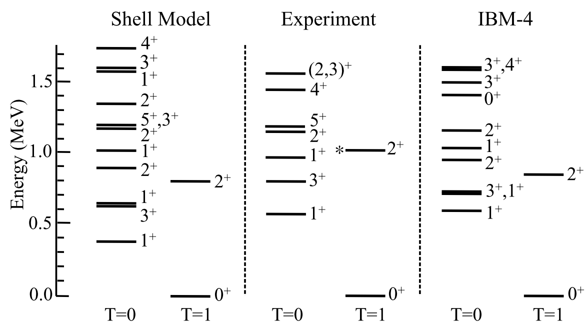

Fig. 4. Experimentally observed low-lying energy levels compared with shell-model [8,13] and IBM-4 model calculations [8]. *See text for detailed discussion regarding the isospin assignment of this state.

involved in this mapping, except an overall scaling of all interaction matrix elements required for the energy renormalisation attributed to truncation effects in the calculation [8]. It should be noted that the IBM-4 calculation does not include high-spin, $T = 0$ bosons. Hence, for example, the yrast 5^+ state obtained in the shell-model calculation is not present.

Levels of agreement between theory and experiment are good at low excitation energies, with all of the predicted lowest-lying, $T = 0$ levels with $I^\pi = 1^+$–5^+ now reported. Juillet et al. caution that the lowest-lying $T = 0$, 0^+ state predicted by the IBM-4 calculation, which is much lower in energy than the shell-model result, may have "an important spurious component" [8]. In any event, as this level would be highly non-yrast and unlikely to be fed in heavy-ion fusion reactions, there is no implied conflict between theory and experiment by its non-observation. The relative ordering of the lowest-lying states is well reproduced by theory, although differences in absolute energies are evident and the calculated level energies are somewhat compressed compared with the empirical observations (see Fig. 4). At excitation energies below 1.5 MeV, at least one predicted $T = 0$, 2^+ level remains unreported, as well as the third 1^+ state. Large-scale shell-model calculations carried out by Petermann et al. [26] predict substantial Gamow–Teller strength to three low-lying 1^+ levels. We note that the γ ray observed at 1247 keV following the β decay of ^{62}Ge [20] suggests a candidate for the third 1^+ state at 1247 keV.

In summary, the majority of the low-lying, $T = 0$ states in the odd–odd, $N = Z$ nucleus ^{62}Ga have now been observed. Good agreement is demonstrated between theory and experiment regarding the level ordering, although calculated energies are shifted with respect to empirical observations. It is clear that there is a dramatic transition between the relatively low level density observed in this $N = Z$ nucleus when compared to neutron-rich, odd–odd Ga isotopes (e.g. ^{64}Ga and ^{68}Ga, for which ~ 30 [27] and ~ 60 [28] states have been observed up to 1.7 MeV, respectively), where configurations with $T = 1$ pairing interactions between excess neutrons are expected to dominate the low-lying level structure [29]. Interesting evidence for such behaviour has been noted for neighbouring heavier odd–odd $N = Z$ nuclei, though in these cases shell-model calculations were not available for comparison with the observed low-lying levels [30]. The present results, therefore, provide a striking example of the special features of $N = Z$ nuclei, which exhibit distinctively different aspects of nuclear structure in comparison to their neighbours.

Acknowledgements

The authors would like to thank Piet Van Isacker for helpful discussions. HMD, PJW, GL, TD and DD wish to acknowledge financial support from the STFC. This work was supported by the US Department of Energy, Office of Nuclear Physics, under contract number DE-AC02-06CH11357.

References

[1] C.B. Hinke, et al., Nature 486 (2012) 345.
[2] C.N. Nesaraja, et al., Nucl. Data Sheets 111 (2010) 897.
[3] A. Poves, G. Martinez-Pinedo, Phys. Lett. B 430 (1998) 203.
[4] D. Dean, S. Koonin, K. Langanke, P. Radha, Phys. Lett. B 399 (1997) 1.
[5] T. Otsuka, T. Mizusaki, M. Honma, J. Phys. G 25 (1999) 699.
[6] A.L. Goodman, Phys. Rev. C 60 (1999) 014311.
[7] J. Dobes, S. Pittel, Phys. Rev. C 57 (1998) 688.
[8] O. Juillet, P. Van Isacker, D.D. Warner, Phys. Rev. C 63 (2001) 054312.
[9] R.S. Simon, et al., Z. Phys. A 325 (1986) 197.
[10] E.S. Paul, et al., Phys. Rev. C 51 (1995) 78.
[11] B.S. Nara Singh, Phys. Rev. C 75 (2007), 061301(R).
[12] A.N. Steer, Nucl. Instrum. Methods A 565 (2006) 630.
[13] S.M. Vincent, et al., Phys. Lett. B 437 (1998) 264.
[14] D. Rudolph, et al., Phys. Rev. C 69 (2004) 034309.
[15] I.Y. Lee, Prog. Part. Nucl. Phys. 38 (1997) 65.
[16] R.V.F. Janssens, F.S. Stephens, Nucl. Phys. News Int. 6 (4) (1996) 9.
[17] C.N. Davids, et al., Nucl. Instrum. Methods B 70 (1992) 358.
[18] J.T. Anderson, et al., IEEE Trans. Nucl. Sci. 56 (2009) 1.
[19] G. Grinyer, et al., Phys. Rev. C 77 (2008) 015501.
[20] E. Grodner, et al., GSI Scientific Reports, 2009, NUSTAR-EXPERIMENTS-16.
[21] T. Steinhardt, Diploma thesis, University of Cologne, 1997, unpublished.
[22] A.F. Lisetskiy, et al., Phys. Rev. C 60 (1999) 064310.
[23] P. Finlay, et al., Phys. Rev. C 78 (2008) 025502.
[24] A.L. Nichols, et al., Nucl. Data Sheets 113 (2012) 973.
[25] E. Caurier, et al., Phys. Rev. C 77 (1996) 1954.
[26] I. Petermann, et al., Eur. Phys. J. A 34 (2007) 319.
[27] B. Singh, Nucl. Data Sheets 108 (2007) 197.
[28] E.A. McCutchan, Nucl. Data Sheets 113 (2012) 1735.
[29] A. Juodagalvis, S. Åberg, Nucl. Phys. A 683 (2001) 207.
[30] D.G. Jenkins, et al., Phys. Rev. C 65 (2002) 064307.